

# Higgs Production by Gluon initiated Weak Boson Fusion

M. M. Weber<sup>1</sup>

1- Department of Physics, University at Buffalo  
The State University of New York, Buffalo, NY 14260-1500, USA

The gluon-gluon induced terms for Higgs production through weak-boson fusion are calculated. They form a finite and gauge-invariant subset of the NNLO corrections in the strong coupling constant. This is also the lowest order with sizeable t-channel colour exchange contributions, leading to additional hadronic activity between the outgoing jets.

## 1 Introduction

The weak-boson-fusion (WBF) process  $qq' \rightarrow qq'H$  is one of the major Higgs-boson production processes at the LHC. With a cross section of up to 20% of the leading gluon fusion process for low Higgs masses it allows a discovery of the Higgs boson in the intermediate mass range as well as for high masses [2, 3]. Furthermore it allows for precise measurements of the Higgs couplings.

Weak-boson fusion has a characteristic signature that can be used to separate it well from the background processes [4]. Since the LO diagrams do not contain t-channel exchange of coloured particles the final-state quarks appear as jets in opposite hemispheres at high rapidities. In the central region between the jets there is very little hadronic activity, only the Higgs decay products are found here.

At NLO the QCD corrections to total rates [5, 6] and the differential cross section [7, 8] have been calculated. They increase the cross section at the LHC by about 10% while reducing the residual scale dependence to about 3%. Colour exchange contributions are strongly suppressed at NLO since diagrams with t-channel gluon exchange contribute only through their interference with u-channel Born diagrams. Since the interference between t- and u-channel diagrams is very small it is usually neglected. In this approximation there are no colour exchange contributions even at NLO and the corrections can be expressed in terms of the structure functions of deep inelastic scattering. Recently also the NLO electroweak corrections and the QCD corrections to the interference terms and have been calculated [9].

Contributions with sizeable t-channel colour exchange can first appear at NNLO. Although at this order gluon or quark pairs can be exchanged between the quark lines, the non-colour-singlet part contributes only in the interference with u-channel diagrams and can therefore be expected to be tiny. Another part of the NNLO corrections is the square of the  $\mathcal{O}(\alpha_s)$  amplitudes. In this contribution non-suppressed diagrams with net colour exchange may appear leading to a possible deviation from the characteristic signature of WBF. Furthermore the NNLO corrections might be larger than could be expected from a naive extrapolation of the NNLO DIS results.

In order to assess the size of these effects we have studied the process  $gg \rightarrow q\bar{q}H$  and the crossed processes  $q\bar{q} \rightarrow ggH$ ,  $qg \rightarrow qgH$  and  $\bar{q}g \rightarrow \bar{q}gH$  [10]. The amplitude is of  $\mathcal{O}(\alpha_s)$  and its square therefore contributes to WBF at NNLO. Since these are loop induced processes appearing first in this order, they are a UV-finite and gauge-invariant subset of the full

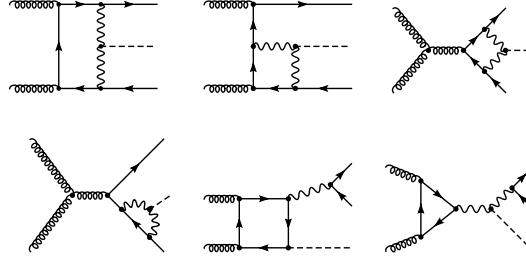


Figure 1: Sample diagrams for the process  $gg \rightarrow q\bar{q}H$ .

NNLO corrections. Due to the large gluon luminosity at the LHC they can also be expected to constitute a sizeable part of the complete NNLO corrections.

The same process also appears in the real-emission corrections to Higgs production in gluon fusion at NNLO. The production of the resulting H+2jet final states has been studied in [11]. However, since these diagrams are of a different order in the coupling constant we will not consider them in this work.

## 2 Computational Framework

An overview of the calculation using the process  $gg \rightarrow q\bar{q}H$  as an example is given in the following. A full description of the complete calculation can be found in Ref. [10]. Some sample 1-loop diagrams are shown in Figure 1. We treat the quarks including the b-quark as massless, and always sum over all 5 light flavours. With this approximation the Higgs boson couples only to the weak gauge bosons and to closed top-quark loops.

The last two diagrams belong to a class containing a virtual Z-boson splitting into a final state  $q\bar{q}$  pair. These diagrams form a gauge-invariant subset. The Z-boson may become resonant and this class then describes  $HZ$  production with a subsequent  $Z \rightarrow q\bar{q}$  decay. Consequently these diagrams belong to the NNLO corrections to the Higgsstrahlung process  $q\bar{q} \rightarrow HZ$  and have to be taken into account there. Since we are only interested in WBF this diagram class is discarded in the following.

Furthermore some diagrams are part of real corrections to lower order Higgs-production processes. Since these are singular in the soft and collinear parts of the phase space we require the two final-state quarks to form two well-resolved jets. With this restriction all diagrams are IR finite over the whole remaining phase space and one obtains a well-defined total rate.

Technically the most challenging part of the calculation are the 5-point diagrams like the first one in Figure 1. These diagrams are similar to the ones appearing in the recent calculation of the electroweak corrections to the process  $e^+e^- \rightarrow \nu\bar{\nu}H$  [12] and the same techniques can also be applied in this case.

The actual calculation of the diagrams has been performed using the 't Hooft–Feynman gauge. The graphs were generated by *FeynArts* [13] and the evaluation of the amplitudes performed using *FormCalc* [14]. The analytical results of *FormCalc* in terms of Weyl-spinor chains and coefficients containing the tensor loop integrals have been translated to C++ code for the numerical evaluation. The tensor and scalar 5-point functions are reduced to 4-point functions following Ref. [15], where a method for a direct reduction is described that avoids

leading inverse Gram determinants which can cause numerical instabilities. The remaining tensor coefficients of the one-loop integrals are recursively reduced to scalar integrals with the Passarino–Veltman algorithm [16] for non-exceptional phase-space points. In the exceptional phase-space regions the reduction of the 3- and 4-point tensor integrals is performed using the methods of Ref. [17] which allow for a numerically stable evaluation.

The phase-space integration is performed with Monte Carlo techniques using the adaptive multi-dimensional integration program VEGAS [18].

### 3 Numerical Results

To study the impact of the contribution calculated here we compare the total cross section to the LO result for WBF. In order to get a well defined total rate we always employ a minimal set of cuts. These minimal cuts ensure two well-separated jets in the final state and are given by

$$p_{T_j} > 20 \text{ GeV}, \quad |\eta_j| < 5, \quad R > 0.6,$$

where  $p_{T_j}$  and  $\eta_j$  are the transverse momenta and the pseudorapidities of the final state jets emerging from the quarks and gluons and

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

with  $\Delta\eta = \eta_1 - \eta_2$  and  $\Delta\phi = \phi_1 - \phi_2$  is the separation of the jets in the pseudorapidity–azimuthal angle plane.

A much improved signal-to-background ratio for weak-boson fusion can be obtained by further cuts [4]. These additional WBF cuts require that the two jets are well separated, reside in opposite detector hemispheres and have a large dijet invariant mass

$$|\Delta\eta| > 4.2, \quad \eta_1 \cdot \eta_2 < 0, \quad m_{jj} > 600 \text{ GeV}.$$

The total cross section summed over all crossed processes is shown on the l.h.s of Figure 2 as a function of the Higgs-boson mass. With only the minimal cuts employed the total rate is about 70 fb for low Higgs masses and falls off steeply towards higher masses. At  $m_H = 100 \text{ GeV}$  this amounts to about 2% of the LO cross section for WBF which is in accordance with the naive expectation for the order of magnitude of the NNLO corrections. The decrease of the cross section toward higher  $m_H$  is however much steeper for the  $gg \rightarrow q\bar{q}H$  process than the rather moderate decrease of the LO result.

The effect of the additional WBF cuts is a strong suppression of the cross section by roughly a factor 30. This strong suppression is in contrast to the LO and NLO WBF rates which only show a suppression by about a factor of 2–3. As the WBF cuts are designed to take advantage of the characteristic signature of weak-boson fusion, this indicates that the kinematics of the contribution investigated here is rather different than the normal WBF kinematics.

The cross sections for the separate processes using WBF cuts are shown on the r.h.s of Figure 2. The largest contribution comes from the process  $qg \rightarrow qgH$  while all other processes are at least a factor of 3 smaller.

In order to shed more light on the origin of the strong suppression caused by the WBF cuts the behaviour of the quantities appearing in the cuts has to be investigated. Therefore the distributions in the pseudorapidity separation  $\Delta\eta$  and the jet-jet invariant mass  $m_{jj}$  are

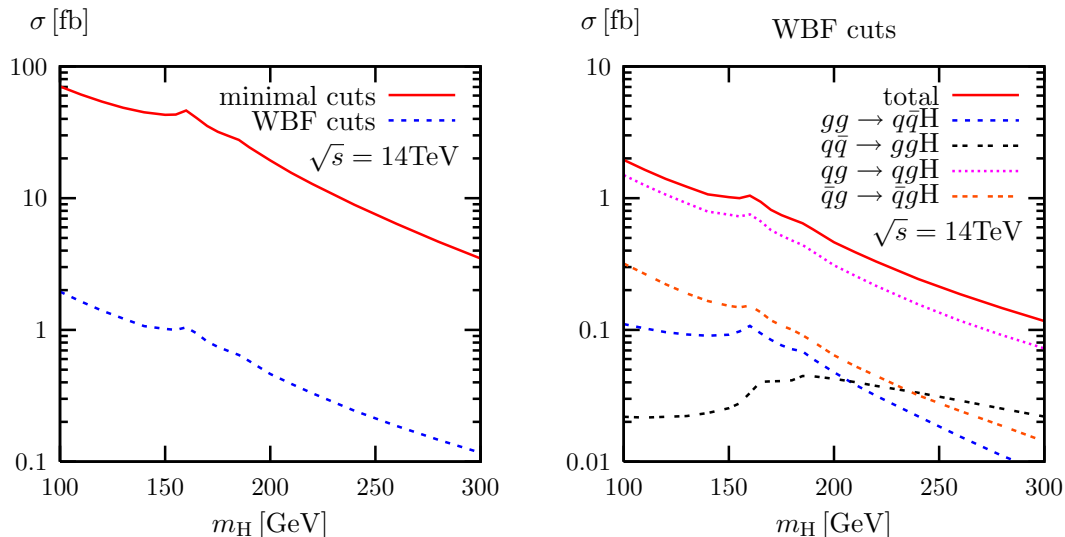


Figure 2: Total cross section summed over all processes with minimal cuts and WBF cuts applied (l.h.s) and separate contributions of all processes using WBF cuts (r.h.s).

shown in Figure 3 for a Higgs mass of  $m_H = 120$  GeV. The pseudorapidity-separation is peaked at low values of about 1 which is much lower than the corresponding peak for the LO result located at  $\Delta\eta \simeq 4$  [7, 8]. The invariant mass distribution falls off fast with increasing  $m_{jj}$ . This falloff is stronger than for WBF at leading order. This shows that the jets are less well separated than for the LO WBF and therefore suffer a stronger suppression by the additional WBF cuts.

## 4 Summary

We have performed a calculation of the loop-induced process  $gg \rightarrow q\bar{q}H$  and the crossed processes. These are a gauge-invariant and finite part of the NNLO corrections to weak-boson fusion featuring t-channel colour exchange, which is strongly suppressed at lower orders. The total cross section is about 70 fb at  $m_H = 100$  GeV and falls off towards higher Higgs masses. Imposing further cuts commonly used to separate the weak-boson-fusion signal from background leads to a strong suppression of the total rates by about a factor of 30. An investigation of distributions has shown this to be caused by different kinematics than for the leading-order weak-boson-fusion process.

## Acknowledgements

We thank Ansgar Denner for supplying us with his Fortran library for the evaluation of the scalar and tensor loop integrals.

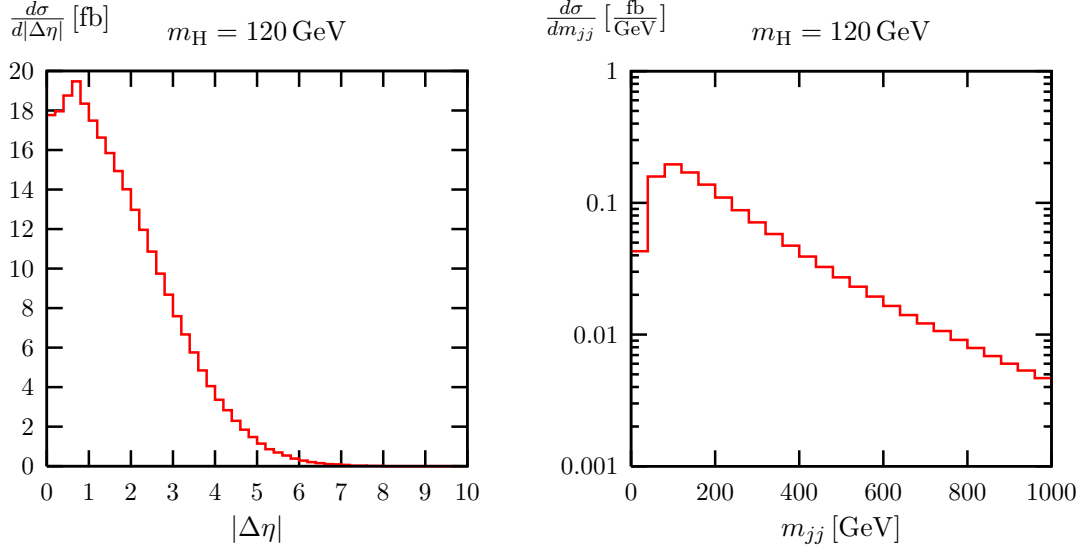


Figure 3: Distribution in the pseudorapidity separation of the quark jets (l.h.s) and the jet-jet invariant mass (r.h.s) for a Higgs mass  $m_H = 120$  GeV.

## References

- [1] Slides:  
<http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=409&sessionId=73&confId=1296>
- [2] S. Asai *et al.*, Eur. Phys. J. C **32S2** (2004) 19 [arXiv:hep-ph/0402254].
- [3] S. Abdullin *et al.*, Eur. Phys. J. C **39S2** (2005) 41.
- [4] D. L. Rainwater, R. Szalapski and D. Zeppenfeld, Phys. Rev. D **54** (1996) 6680 [arXiv:hep-ph/9605444];  
D. L. Rainwater and D. Zeppenfeld, Phys. Rev. D **60** (1999) 113004 [Erratum-ibid. D **61** (2000) 099901]  
[arXiv:hep-ph/9906218]; T. Plehn, D. L. Rainwater and D. Zeppenfeld, Phys. Rev. D **61** (2000) 093005  
[arXiv:hep-ph/9911385].
- [5] T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. **69** (1992) 3274 [arXiv:hep-ph/9206246].
- [6] A. Djouadi and M. Spira, Phys. Rev. D **62** (2000) 014004 [arXiv:hep-ph/9912476].
- [7] T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D **68** (2003) 073005 [arXiv:hep-ph/0306109].
- [8] E. L. Berger and J. Campbell, Phys. Rev. D **70** (2004) 073011 [arXiv:hep-ph/0403194].
- [9] M. Ciccolini, A. Denner and S. Dittmaier, arXiv:0707.0381 [hep-ph].
- [10] R. Harlander, J. Vollinga and M. M. Weber, in preparation.
- [11] V. Del Duca, W. Kilgore, C. Oleari, C. Schmidt and D. Zeppenfeld, Nucl. Phys. B **616** (2001) 367  
[arXiv:hep-ph/0108030] and Phys. Rev. Lett. **87** (2001) 122001 [arXiv:hep-ph/0105129].
- [12] A. Denner, S. Dittmaier, M. Roth and M. M. Weber, Phys. Lett. B **560** (2003) 196 [hep-ph/0301189]  
and Nucl. Phys. B **660** (2003) 289 [hep-ph/0302198].
- [13] T. Hahn, Comput. Phys. Commun. **140** (2001) 418 [hep-ph/0012260].
- [14] T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. **118** (1999) 153 [hep-ph/9807565]; T. Hahn,  
Nucl. Phys. Proc. Suppl. **89** (2000) 231 [hep-ph/0005029].
- [15] A. Denner and S. Dittmaier, Nucl. Phys. B **658** (2003) 175 [hep-ph/0212259].
- [16] G. Passarino and M. Veltman, Nucl. Phys. B **160** (1979) 151.
- [17] A. Denner and S. Dittmaier, Nucl. Phys. B **734** (2006) 62 [arXiv:hep-ph/0509141].
- [18] G. P. Lepage, J. Comput. Phys. **27** (1978) 192 and CLNS-80/447.